
SUSY QCD corrections to squark loops in Higgs boson production via gluon gluon fusion

MMM, M. Spira, hep-ph/0612254

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Physics at TeV Colliders

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Introduction

Gluon gluon fusion: dominant production process at existing and future hadron colliders.

QCD corrections to top & bottom loops

NLO (SM, MSSM): increase σ by $\sim 10\text{...}100\%$ Spira, Djouadi, Graudenz, Zerwas
Dawson; Kauffman, Schaffer

SM, $t\bar{g} \lesssim 5$: limit $M_\Phi \ll m_t$ - approximation $\sim 20\text{-}30\%$ Krämer, Laenen, Spira

NNLO @ $M_\Phi \ll m_t \Rightarrow$ further increase by 20-30% Harlander, Kilgore
Anastasiou, Melnikov
scale dependence: $\Delta \lesssim 10 - 15\%$ Ravindran, Smith, van Neerven

Soft gluon resummation \rightsquigarrow additional +6% Catani, de Florian
Grazzini, Nason

Estimate of NNNLO effects \rightsquigarrow improved perturbative convergence Moch, Vogt
Ravindran

Electroweak two-loop effects \rightsquigarrow +5-8% Aglietti et al.
Degrossi, Maltoni

NLO corrections: to squark loops

only in heavy squark limit Dawson, Djouadi, Spira

full SUSY-QCD corrections in heavy mass limit Harlander, Steinhauser
Harlander, Hofmann

$m_{\tilde{Q}} \lesssim 400 \text{ GeV}$: squarks play a significant role \rightsquigarrow
calculation of the full squark mass dependence at NLO.

The MSSM Higgs sector

MSSM Higgs sector – supersymmetry & anomaly free theory \Rightarrow 2 complex Higgs doublets

EW
 $\xrightarrow{\text{SB}}$

neutral, CP-even h, H

neutral, CP-odd A

charged H^+, H^-

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Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$

$$M_{A,H,H^\pm} \sim \mathcal{O}(v) \dots 1 \text{ TeV}$$

Ellis et al; Okada et al; Haber, Hempfling;
Hoang et al; Carena et al; Heinemeyer et al;
Zhang et al; Brignole et al; ...

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Modified couplings with respect to the SM: (decoupling limit) Gunion, Haber

Φ	$g_{\Phi u\bar{u}}$	$g_{\Phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \rightarrow 1$	$-s_\alpha/c_\beta \rightarrow 1$	$s_{\beta-\alpha} \rightarrow 1$
H	$s_\alpha/s_\beta \rightarrow 1/\text{tg}\beta$	$c_\alpha/c_\beta \rightarrow \text{tg}\beta$	$c_{\beta-\alpha} \rightarrow 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

$$\tan \beta \uparrow \Rightarrow g_{\Phi uu} \downarrow$$

$$g_{\Phi dd} \uparrow$$

$$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$$

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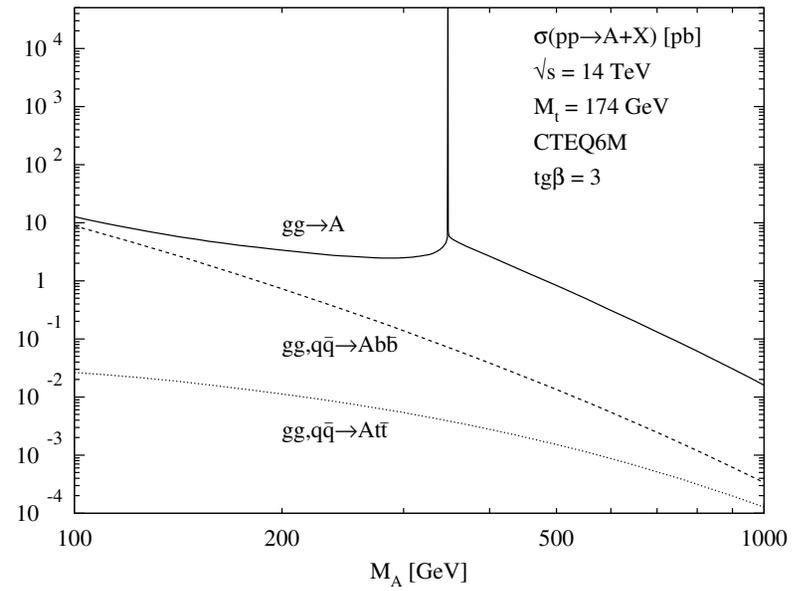
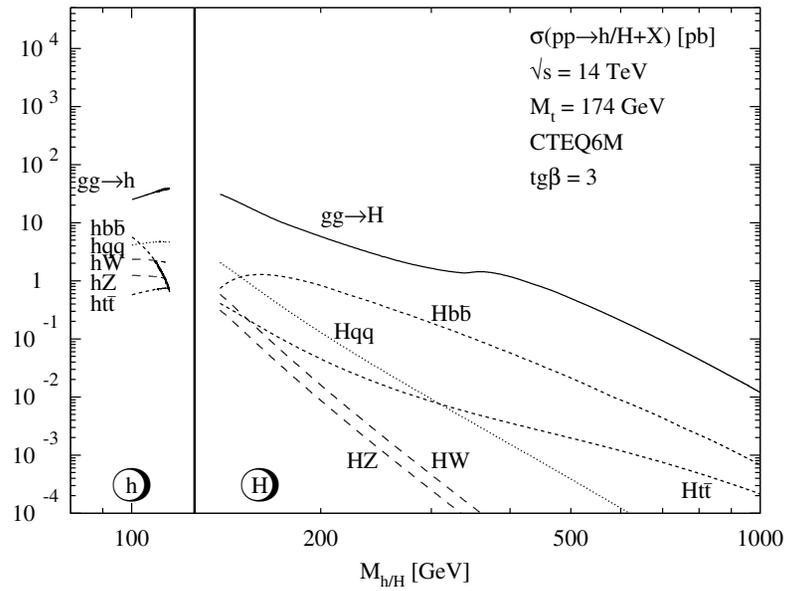
$$\tan \beta \uparrow \Rightarrow g_{\Phi uu} \downarrow$$

$$g_{\Phi dd} \uparrow$$

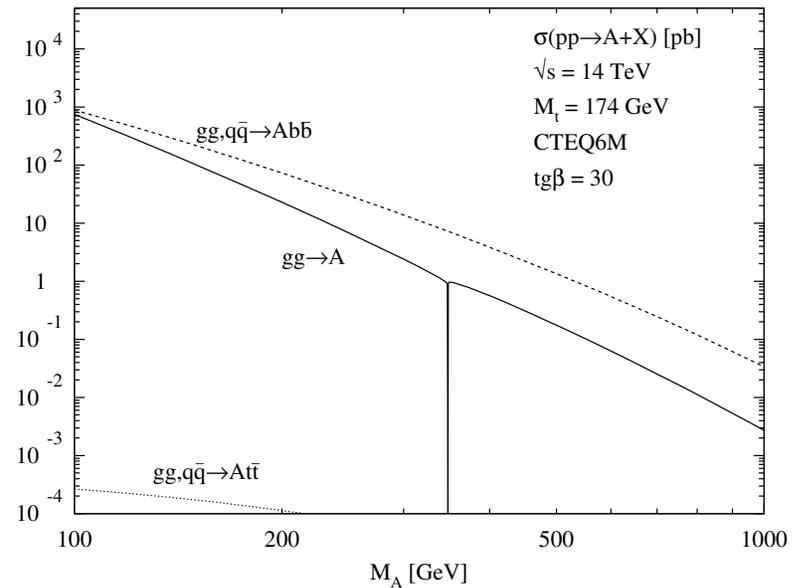
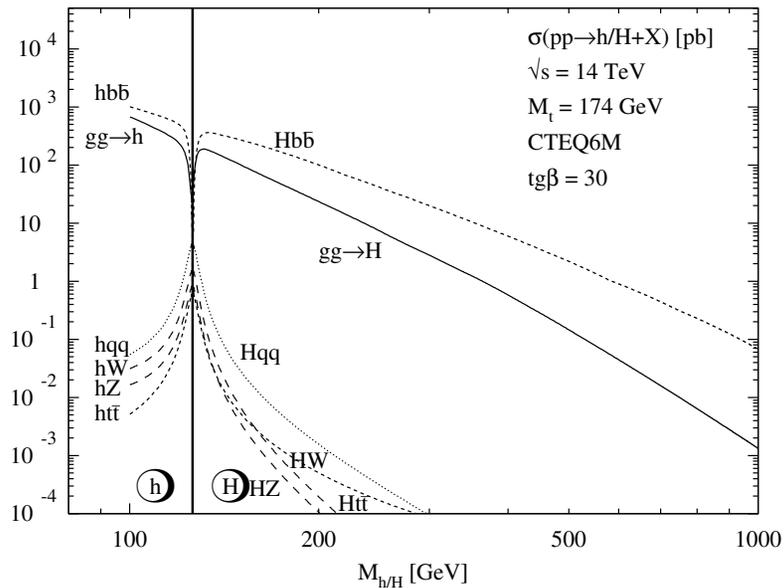
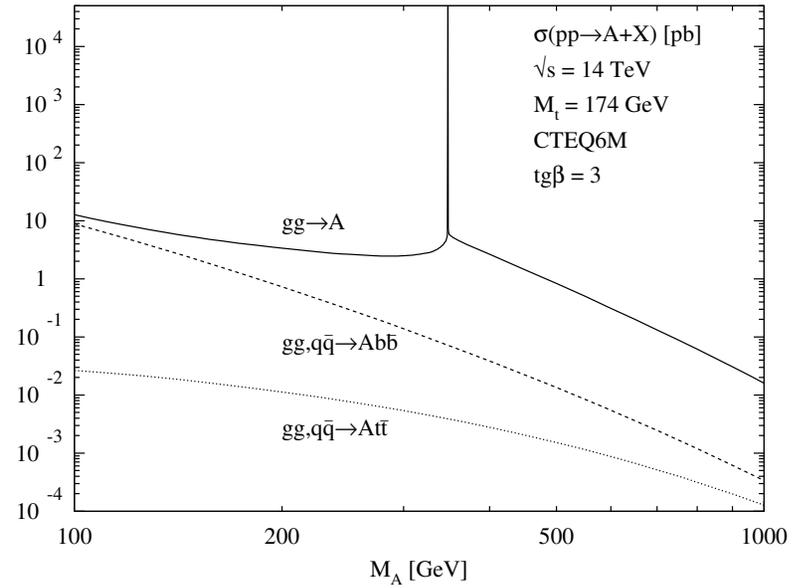
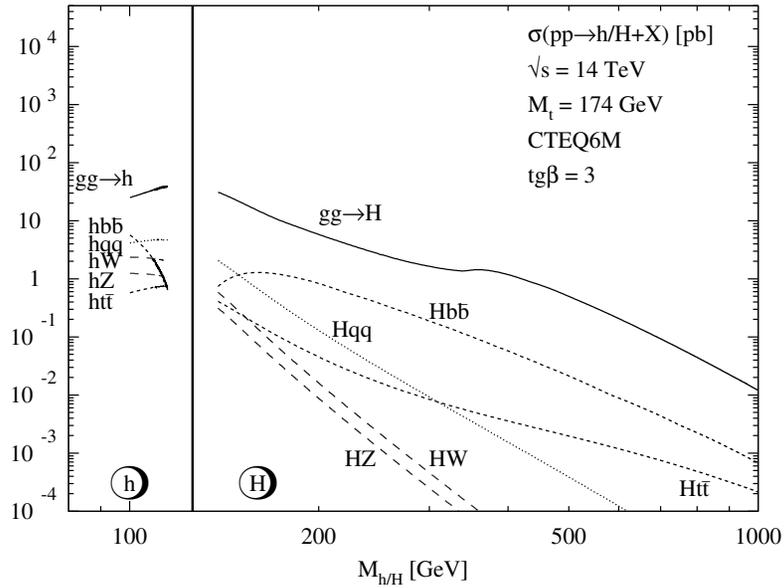
$$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$$

Dominant production mechanism at the LHC: $gg \rightarrow \Phi$
 $\Phi b\bar{b}$ for $\tan \beta$ large

MSSM Higgs boson production at the LHC

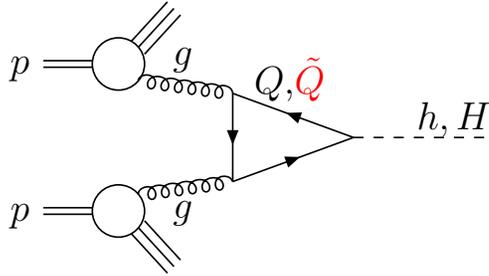


MSSM Higgs boson production at the LHC



gg → H, h at leading order

Lowest order - 1 loop



$$\sigma(pp \rightarrow \Phi + X) = \sigma_0 \tau_\Phi \frac{d\mathcal{L}^{gg}}{d\tau_\Phi}$$

$$\sigma_0 = \frac{G_F \alpha_S^2(\mu_R)}{288\sqrt{2}\pi} \left| \sum_Q g_Q^\Phi F(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^\Phi \tilde{F}(\tau_{\tilde{Q}}) \right|^2$$

$$\tau_\Phi = \frac{M_\Phi^2}{s}, \quad \tau_{Q, \tilde{Q}} = \frac{4m_{Q, \tilde{Q}}^2}{M_\Phi^2}$$

$$F(\tau_Q) = \frac{3}{2} \tau_Q \left[1 + (1 - \tau_Q) f(\tau_Q) \right]$$

$$\tilde{F}(\tau_{\tilde{Q}}) = -\frac{3}{4} \tau_{\tilde{Q}} \left[1 - \tau_{\tilde{Q}} f(\tau_{\tilde{Q}}) \right]$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4} \left[\log \left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} \right) - i\pi \right]^2 & \tau < 1 \end{cases}$$

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x} g(x, \mu_F^2) g(\tau/x, \mu_F^2)$$

Remarks: - MSSM: $\tan \beta \uparrow \Rightarrow b/\tilde{b} \uparrow + t/\tilde{t} \downarrow$

- heavy quarks dominant

$\Phi QQ \sim m_Q \rightsquigarrow t, b$

- $g_{\tilde{Q}}^\Phi \sim m_Q^2/m_{\tilde{Q}}^2 \rightsquigarrow \tilde{t}, \tilde{b}$

- $gg \rightarrow A$ no \tilde{Q} contribution at LO

The scenario

The gluophobic Higgs scenario [$m_t = 174.3$ GeV]

Carena, Heinemeyer, Wagner, Weiglein

$$M_{SUSY} = 350 \text{ GeV}, \mu = M_2 = 300 \text{ GeV}, X_t = -770 \text{ GeV}, A_b = A_t, m_{\tilde{g}} = 500 \text{ GeV}$$

$$\tan \beta = 3$$

$$m_{\tilde{t}_1} = 156 \text{ GeV} \quad m_{\tilde{t}_2} = 517 \text{ GeV}$$

$$m_{\tilde{b}_1} = 346 \text{ GeV} \quad m_{\tilde{b}_2} = 358 \text{ GeV}$$

$$\tan \beta = 30$$

$$m_{\tilde{t}_1} = 155 \text{ GeV} \quad m_{\tilde{t}_2} = 516 \text{ GeV}$$

$$m_{\tilde{b}_1} = 314 \text{ GeV} \quad m_{\tilde{b}_2} = 388 \text{ GeV}$$

Particle masses and couplings - calculated with **SUSY-HIT** \rightsquigarrow "Intermezzo".

SUSY-HIT (SUSpect-SdecaY-Hdecay-Interface)

Djouadi,MMM,Spira, hep-ph/0609292

SUSY-HIT Program package for the calculation of SUSY particle decays within the MSSM.

Based on: **HDECAY** - Γ , BR of MSSM Higgs bosons **SDECAY** - Γ , BR of the SUSY particles
SUSY spectrum: SuSpect or any spectrum code with the **SLHA format** Skands et al.

SDECAY: “phenomenological MSSM” (no CP , no R -parity violation)

- **QCD corrs. to coloured 2-body decays**
- multi-body & loop-induced decays
- top decays
- NSLP decays in GMSB models.
- running strong coupling constant and quark masses: \overline{DR} scheme @ EWSB scale

HDECAY: • higher order corrs. and off-shell decays, including those into SUSY particle final states

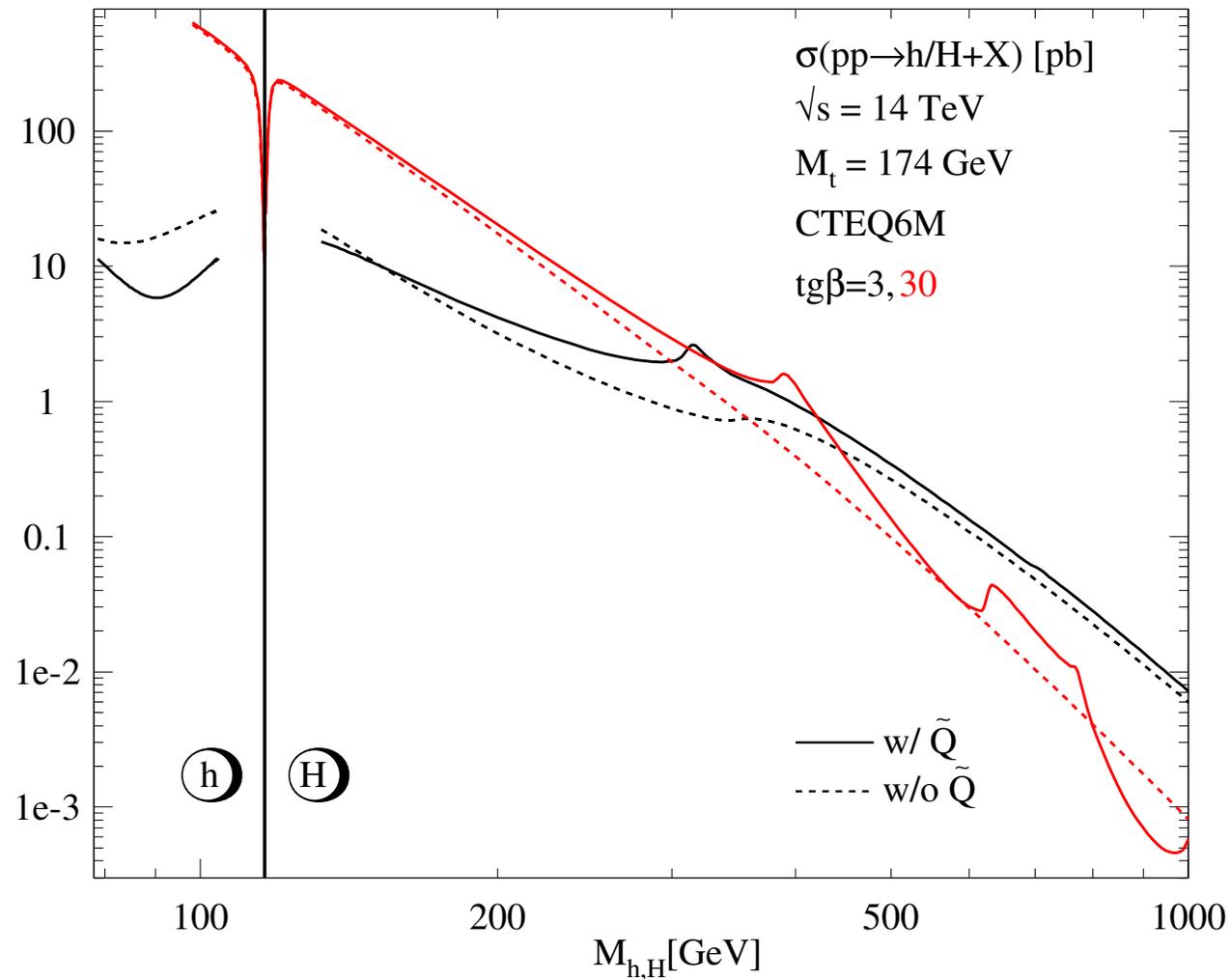
new: • inclusion of SLHA format

remarks: • translation of SLHA \overline{DR} input parameters into \overline{MS} scheme
• Higgs self-couplgs. (not in SLHA input) from effective potential approach

Files: susyhit.in//sdecay.f//hdecay.f,susylha.f//SuSpect files or slhaspectrum.in

Web page: <http://lappweb.in2p3.fr/~muehlleitner/SUSY-HIT/>

The LO cross section w/ and w/o Squarks



QCD corrections

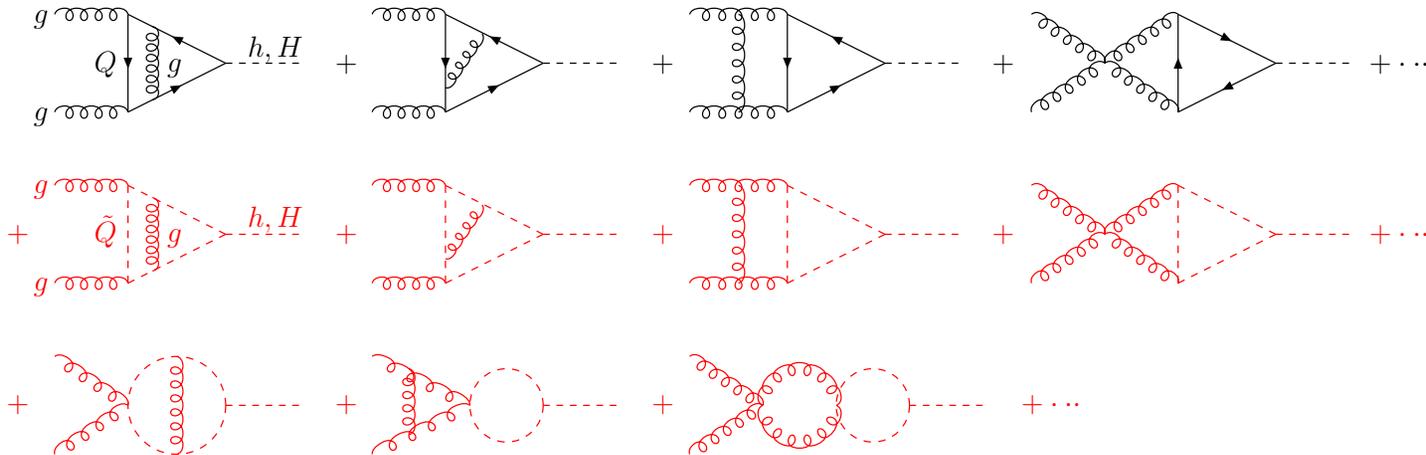
$$\Delta\hat{\sigma}_{ij} = \sigma_0 \left\{ C_{ij}\delta(1 - \hat{\tau}) + D_{ij}\Theta(1 - \hat{\tau}) \right\} \frac{\alpha_s}{\pi}$$

$$\hat{\tau} = \frac{M_{\Phi}^2}{\hat{s}}$$

\nearrow
 virtual+soft
 corrections

\uparrow
 real corrections

Virtual corrections [2 loops, no gluino contributions]



UV-,IR-,Coll-singularities in $n = 4 - 2\epsilon$ dimensions.

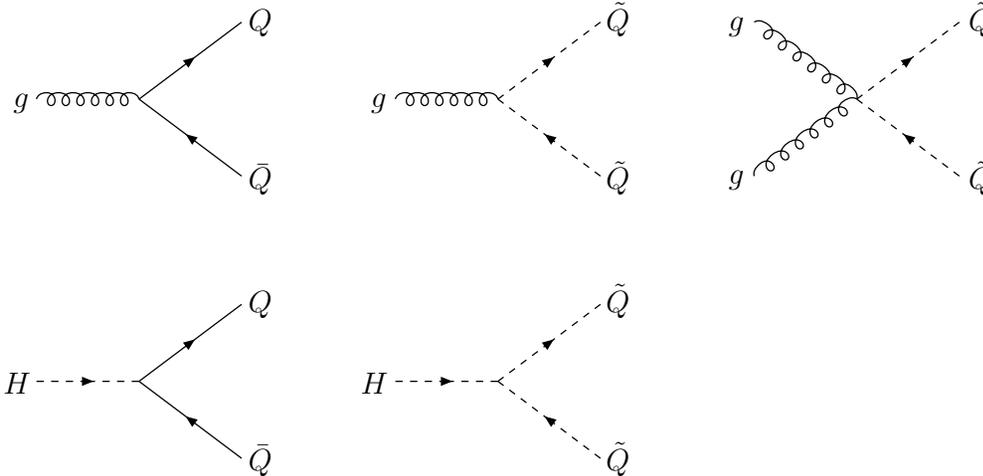
Renormalization

Lagrangian separates gluon and gluino exchange contributions in a renormalizable way

$$\mathcal{L} = -\frac{1}{4}G^{a\mu\nu}G_{\mu\nu}^a + \bar{Q}(i\not{D} - m_Q)Q + |D_\mu\tilde{Q}|^2 - m_{\tilde{Q}}^2|\tilde{Q}|^2 - g_Q^H \frac{m_Q}{v}\bar{Q}QH - g_{\tilde{Q}}^H \frac{m_{\tilde{Q}}^2}{v}|\tilde{Q}|^2H + \frac{1}{2}(\partial_\mu H)^2 - \frac{M_H^2}{2}H^2$$

$$iD_\mu = i\partial_\mu - g_S G_\mu^a T^a$$

Interaction vertices:



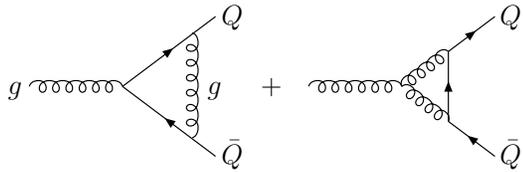
Renormalization - Suite

- Quark/Squark mass $m_{Q,\tilde{Q}}$: on-shell

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- $gQ\bar{Q}$ vertex:



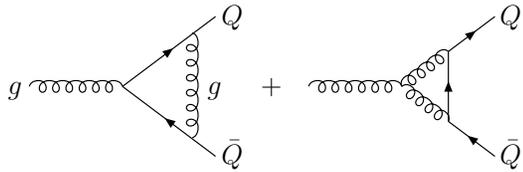
$$Z_1 = Z_{\alpha_S}^{1/2} Z_3^{1/2} Z_2$$

[Slavnov-Taylor identity]

Renormalization - Suite

- Quark/Squark mass $m_{Q,\tilde{Q}}$: on-shell

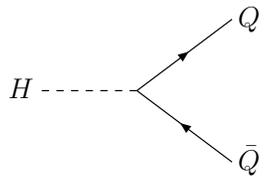
- $gQ\bar{Q}$ vertex:



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[Slavnov-Taylor identity]

- $HQ\bar{Q}$ vertex:



$$\mathcal{L}_{\text{int}} = -g_Q^H \frac{m_{Q_0}}{v} \bar{\Psi}_0 \Psi_0 H = -g_Q^H \frac{m_Q}{v} \bar{\Psi} \Psi H \underbrace{\left[Z_2 - \frac{\delta m_Q}{m_Q} \right]}_{Z_{HQQ}} + \mathcal{O}(\alpha_S^2)$$

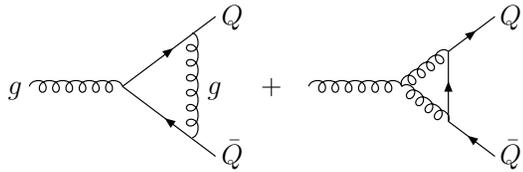
$$\Gamma_{H\bar{Q}Q}(q^2 = 0) \neq Z_{HQQ}$$

Braaten, Leveille

Renormalization - Suite

- Quark/Squark mass $m_{Q,\tilde{Q}}$: on-shell

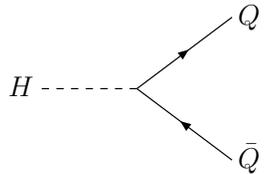
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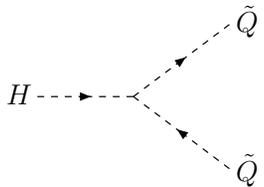


$$\mathcal{L}_{\text{int}} = -g_Q^H \frac{m_{Q_0}}{v} \bar{\Psi}_0 \Psi_0 H = -g_Q^H \frac{m_Q}{v} \bar{\Psi} \Psi H \underbrace{\left[Z_2 - \frac{\delta m_Q}{m_Q} \right]}_{Z_{HQQ}} + \mathcal{O}(\alpha_S^2)$$

$$\Gamma_{H\bar{Q}Q}(q^2 = 0) \neq Z_{HQQ}$$

Braaten, Leveille

- $H\tilde{Q}\tilde{Q}$ vertex:



$$\mathcal{L}_{\text{int}} = -g_{\tilde{Q}}^H \frac{m_{\tilde{Q}_0}^2}{v} \tilde{Q}_0^* \tilde{Q}_0 H = -g_{\tilde{Q}}^H \frac{m_{\tilde{Q}}^2}{v} \tilde{Q}^* \tilde{Q} H \underbrace{\left[Z_2^{\tilde{Q}} - \frac{\delta m_{\tilde{Q}}^2}{m_{\tilde{Q}}^2} \right]}_{Z_{H\tilde{Q}\tilde{Q}}} + \mathcal{O}(\alpha_S^2)$$

$$\Gamma_{H\tilde{Q}\tilde{Q}}(q^2 = 0) \neq Z_{H\tilde{Q}\tilde{Q}}$$

disregard renorm. of $g_{\tilde{Q}}^H$!

Virtual corrections - heavy loop particle mass limit

Total virtual correction [heavy squark/quark limit]:

$$C_{\text{virt}} = \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{M_{\Phi}^2} \right)^{\epsilon} \left\{ -\frac{3}{\epsilon^2} - \frac{33-2N_F}{6\epsilon} \left(\frac{\mu^2}{M_{\Phi}^2} \right)^{-\epsilon} + \pi^2 + \frac{11}{2} + \frac{7}{2} \text{Re} \left\{ \frac{\sum_{\tilde{Q}} g_{\tilde{Q}}^{\Phi} \tilde{F}(\tau_{\tilde{Q}})}{\sum_Q g_Q^{\Phi} F(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^{\Phi} \tilde{F}(\tau_{\tilde{Q}})} \right\} \right\}$$

↑
IR

↑
Coll

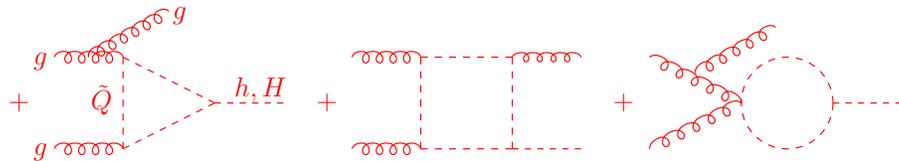
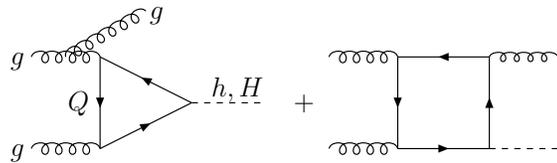
[without squark loops only $\frac{11}{2}$]

To get a finite cross section the real corrections have to be added.

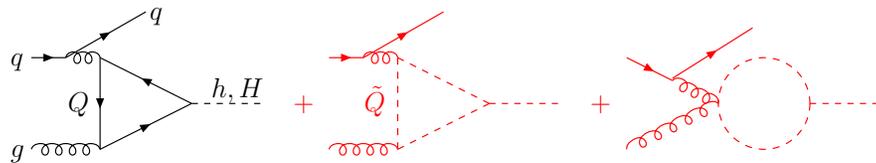
Real Corrections

3 incoherent processes:

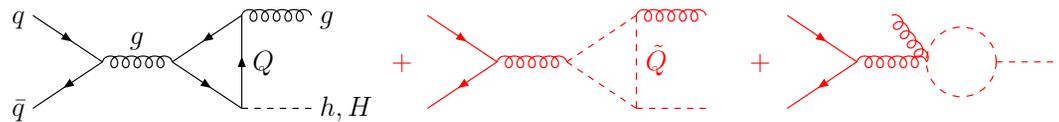
$gg \rightarrow Hg$:



$gq \rightarrow Hq$:



$q\bar{q} \rightarrow Hg$:



Phase space integration in $n = 4 - 2\epsilon$ dimensions \rightsquigarrow IR, Coll. singularities: poles in ϵ

Real corrections - heavy loop particle mass limit

Total real corrections [heavy squark/quark limit]:

$$C_{\text{real}} = \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{m_\Phi^2} \right)^\epsilon \left\{ \frac{3}{\epsilon^2} + \frac{33-2N_F}{6\epsilon} \right\}$$

$$D_{gg} = -\frac{\hat{\tau}}{\epsilon} \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{\hat{s}} \right)^\epsilon P_{gg}(\hat{\tau}) - \frac{11}{2}(1-\hat{\tau})^3 \\ + 12 \left\{ \left(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}} \right)_+ - \hat{\tau}[2-\hat{\tau}(1-\hat{\tau})] \log(1-\hat{\tau}) \right\}$$

$$D_{gq} = -\left\{ \frac{1}{2\epsilon} \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{\hat{s}} \right)^\epsilon - \log(1-\hat{\tau}) \right\} \hat{\tau} P_{gq}(\hat{\tau}) - 1 + 2\hat{\tau} - \frac{\hat{\tau}^2}{3}$$

$$D_{q\bar{q}} = \frac{32}{27}(1-\hat{\tau})^3$$

- IR, Coll. poles in C_{real} subtract the corresponding ones of the virtual corrections.
- Coll. poles in the real corrections (Altarelli-Parisi kernels as coefficients)
~> absorbed in NLO structure functions.

Result - heavy loop particle mass limit

$$\sigma(pp \rightarrow \Phi + X) = \sigma_0 \left[1 + C \frac{\alpha_S}{\pi} \right] \tau_\Phi \frac{d\mathcal{L}_{gg}}{d\tau_\Phi} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$

$$C = \pi^2 + \frac{11}{2} + \frac{7}{2} \operatorname{Re} \left\{ \frac{\sum_{\tilde{Q}} g_{\tilde{Q}}^\Phi \tilde{F}(\tau_{\tilde{Q}})}{\sum_Q g_Q^\Phi F(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^\Phi \tilde{F}(\tau_{\tilde{Q}})} \right\} + \frac{33-2N_F}{6} \log \frac{\mu^2}{M_\Phi^2}$$

$$\Delta\sigma_{gg} = \int_{\tau_\Phi}^1 d\tau \frac{d\mathcal{L}_{gg}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \left\{ -\hat{\tau} P_{gg}(\hat{\tau}) \log \frac{Q^2}{\hat{s}} - \frac{11}{2} (1 - \hat{\tau})^3 \right. \\ \left. + 12 \left[\left(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}} \right)_+ - \hat{\tau} [2 - \hat{\tau}(1 - \hat{\tau})] \log(1 - \hat{\tau}) \right] \right\}$$

$$\Delta\sigma_{gq} = \int_{\tau_\Phi}^1 d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}_{gq}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \left\{ -\frac{\hat{\tau}}{2} P_{gq}(\hat{\tau}) \left[\log \frac{Q^2}{\hat{s}} - 2 \log(1 - \hat{\tau}) \right] \right. \\ \left. - 1 + 2\hat{\tau} - \frac{\hat{\tau}^2}{3} \right\}$$

$$\Delta\sigma_{q\bar{q}} = \int_{\tau_\Phi}^1 d\tau \sum_q \frac{d\mathcal{L}_{q\bar{q}}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \frac{32}{27} (1 - \hat{\tau})^3$$

$[\mu = \text{Ren. scale}, Q = \text{Fact. scale}]$

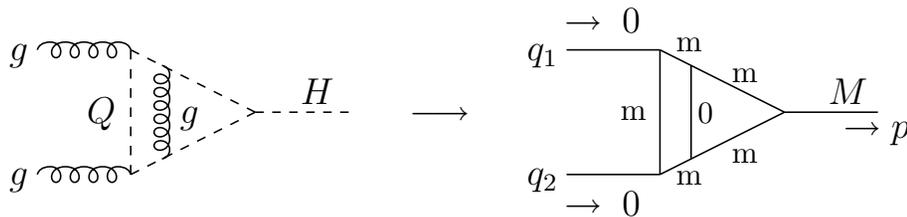
natural scales: $\mu^2 = Q^2 = M_\Phi^2$

General case (arbitrary $M_\Phi, m_Q, m_{\tilde{Q}}$)

- Interference $b, t, \tilde{b}, \tilde{t}$
- 5-dim. Feynman integrals \rightarrow 1-dimensional [Trilogarithms] + purely numerical solution

(analytically: Harlander, Kant
Anastasiou, Beerli, Bucherer, Daleo, Kunszt)
Aglietti, Bonciani, Degrassi, Vicini

Example:



$$S = \int \frac{d^n k d^n q}{(2\pi)^{2n}} \frac{1}{(k^2 - m^2)[(k - q_1)^2 - m^2][(k + q_2)^2 - m^2][(k + q - q_1)^2 - m^2][(k + q + q_2)^2 - m^2]q^2}$$

$$= -\frac{\Gamma(2 + 2\epsilon)}{(4\pi)^4 m^4} \left(\frac{4\pi\mu^2}{m^2}\right)^{2\epsilon} \times I$$

$$I = \int_0^1 dx dy dz dr ds \frac{xz}{N^2} \qquad \rho = \frac{M_\Phi^2}{m_{\tilde{Q}}^2} (1 + i0)$$

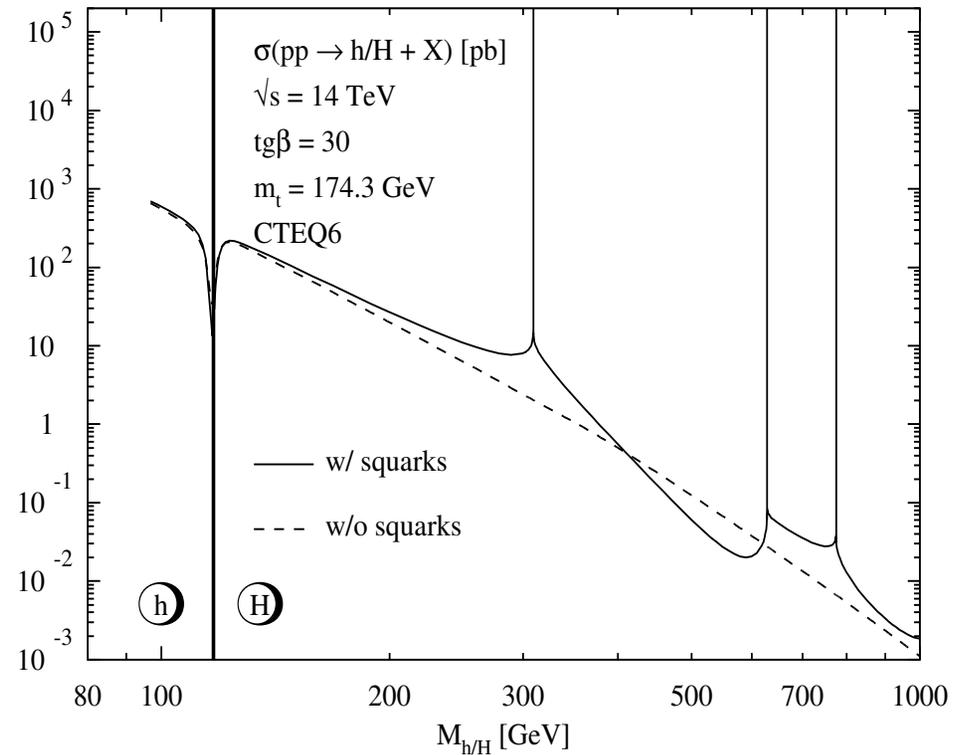
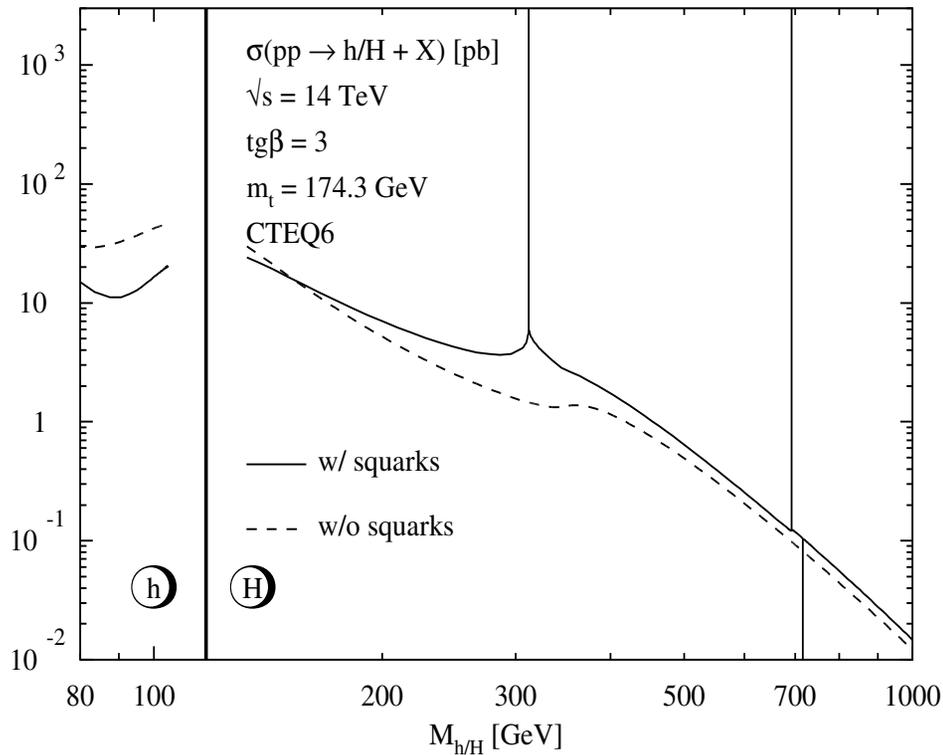
$$N = 1 + \rho \{ rx(1-x)(1-y-z)(1-y-zs) - [y + (1-y-z)x][1-y-x(1-y-zs)] \}$$

Result

- α_S : $\overline{\text{MS}}$ scheme, 5 active flavours
- $\lim_{m_{\tilde{Q}} \rightarrow \infty}$ recovered
- calculation analogous to $m_{\tilde{Q}} \rightarrow \infty$

$$\begin{aligned}
 \sigma(pp \rightarrow \Phi + X) &= \sigma_0 \left[1 + C \frac{\alpha_S}{\pi} \right] \tau_\Phi \frac{d\mathcal{L}_{gg}}{d\tau_\Phi} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}} \\
 C &= \pi^2 + C_1(\tau_Q, \tau_{\tilde{Q}}) + \frac{33-2N_F}{6} \log \frac{\mu^2}{M_\Phi^2} \\
 \Delta\sigma_{gg} &= \int_{\tau_\Phi}^1 d\tau \frac{d\mathcal{L}_{gg}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \left\{ -\hat{\tau} P_{gg}(\hat{\tau}) \log \frac{Q^2}{\hat{s}} + d_{gg}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \right. \\
 &\quad \left. + 12 \left[\left(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}} \right)_+ - \hat{\tau} [2 - \hat{\tau}(1-\hat{\tau})] \log(1-\hat{\tau}) \right] \right\} \\
 \Delta\sigma_{gq} &= \int_{\tau_\Phi}^1 d\tau \sum_{q, \bar{q}} \frac{d\mathcal{L}_{gq}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \left\{ -\frac{\hat{\tau}}{2} P_{gq}(\hat{\tau}) \left[\log \frac{Q^2}{\hat{s}} - 2 \log(1-\hat{\tau}) \right] \right. \\
 &\quad \left. + d_{gq}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \right\} \\
 \Delta\sigma_{q\bar{q}} &= \int_{\tau_\Phi}^1 d\tau \sum_q \frac{d\mathcal{L}_{q\bar{q}}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 d_{q\bar{q}}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}})
 \end{aligned}$$

The NLO cross section w/ and w/o Squarks



$\Delta_{\tilde{q}} \sim 100 - 200\%$

Kinks, bumps, spikes: $\tilde{t}_1\tilde{t}_1, t\bar{t}, \tilde{b}_1\tilde{b}_1, \tilde{b}_2\tilde{b}_2$ thresholds in consecutive order with rising Higgs mass.

Coulomb singularities

$\tilde{Q}\bar{Q}$ thresholds: Formation of 0^{++} states \rightsquigarrow Coulomb singularities

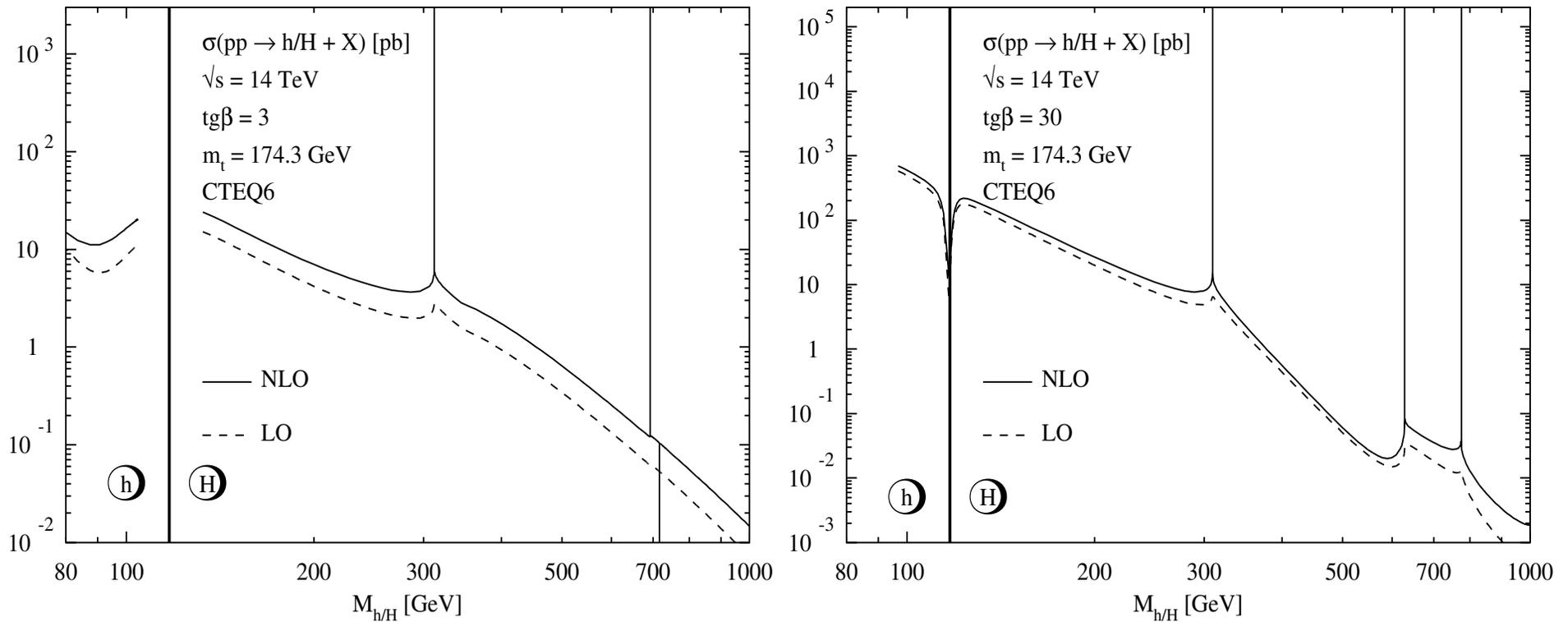
Singular behaviour can be derived from the Sommerfeld rescattering corrections \rightsquigarrow

At each specific $\tilde{Q}_0\bar{Q}_0$ threshold:

$$C_1(\tau_Q, \tau_{\tilde{Q}}) \rightarrow \text{Re} \left\{ \frac{g_{\tilde{Q}_0}^{\Phi} \tilde{F}(\tilde{Q}_0) \frac{16\pi^2}{3(\pi^2-4)} \left[-\ln(\tau_{\tilde{Q}_0}^{-1}-1) + i\pi + \text{const} \right]}{\sum_Q g_Q^{\Phi} F(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^{\Phi} \tilde{F}(\tau_{\tilde{Q}})} \right\}$$

Agrees quantitatively with numerical results.

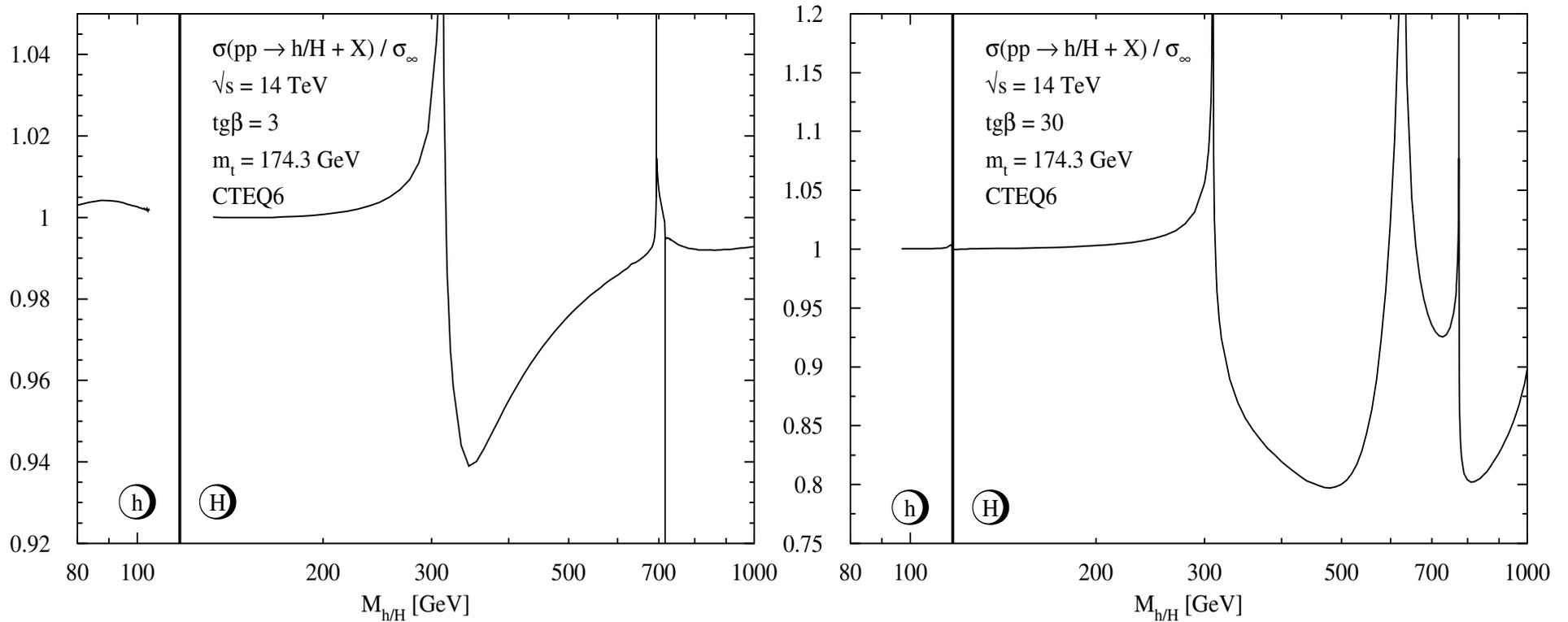
The LO and NLO cross section w/ Squarks



$\Delta \sim 20 - 100\%$

Kinks, bumps, spikes: $\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1, \tilde{b}_2\tilde{b}_2$ thresholds in consecutive order with rising Higgs mass.

σ_{NLO} w/ full squark mass dependence / σ_{NLO} in the heavy squark limit



$\sigma(pp \rightarrow h/H + X) / \sigma_\infty$ up to 20%

Kinks, bumps, spikes: $\tilde{t}_1\tilde{t}_1, \tilde{b}_1\tilde{b}_1, \tilde{b}_2\tilde{b}_2$ thresholds in consecutive order with rising Higgs mass.

Conclusions

- Calculated NLO corrections to $gg \rightarrow h, H$ including the full squark mass dependence.
- K-factor with squarks included is large.
- K-factor very similar to the case of quark loops alone \rightsquigarrow large corrections to squark loops, too.
- Inclusion of full squark mass dependence has significant effects on the K-factor compared to the heavy squark mass limit. The deviation can be as large as $\mathcal{O}(20\%)$.

Note: 2 independent papers by Anastasiou, Beerli, Bucherer, Daleo, Kunszt :
Aglietti, Bonciani, Degrandi, Vicini

Virtual corrections to quark & squark loops in gg fusion derived analytically.
However, no full numerical analysis of the gluon fusion processes at NLO.